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SUMMARY REPORT FOR THE PERIOD 1 JULY 1963 THRU 30 JUNE 1964 MECHANICS OF GEYSERING OF CRYOGENICS

June 1964

MARTIN COMPANY
DENVER, COLORADO
AEROSPACE DIVISION OF MARTIN-MARIETTA CORPORATION

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FOREWORD

The report is submitted in response to Contract NAS8-5418.

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SUMMARY

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This report describes the work performed from 1 July 1963 thru 30 June 1964, in accordance with Marshall Space Flight Center (MSFC) Contract NAS8-5418 for the study of the mechanics of geysering of cryogenics.

The study consisted of developing a method for the prediction of geysering and nongeysering combinations of system geometry, fluid properties, and heating rate. An experimental program, based on work done by others in conjunction with free convection cooling of turbine blades, was conducted, which resulted in an empirical correlation for the prediction of geysering. This correlation was based on the results of 114 geyser tests using water, Freon 113, liquid nitrogen, and liquid hydrogen as test fluids.

Geyser tubes of 4-, 6-, 8-, and 13-in.-diameter and geyser tubes with length to diameter ratios of 1.5 to 30 were investigated. The heat flux range studied was between 50 and 2100 Btu/ft^2-hr.

In addition, a limited effort was expended to qualitatively investigate the feasibility of four methods of geyser suppression. The four methods were:

1) Base heating;

2) Horizontal tube at the base of the geyser tube;

3) Concentrated heat flux on the geyser tube;

4) Concentric tube in the geyser tube.

The first and third methods showed no promise as suppression methods; the second and fourth methods under limited circumstances were successful in suppressing geysering.

Author

NOMENCLATURE

k	fluid thermal conductivity (Btu/ft hr °F)
β	fluid coefficient of cubic expansion (1/°F)
C_p	fluid density $\left(lb_m/ft^3\right)$
μ	fluid viscosity $\left(lb_m/ft\ hr\right)$
g	acceleration of gravity $\left(4.18 \times 10^8\ ft/hr^2\right)$
ν	fluid kinematic viscosity $\left(ft^2/hr\right)$
α	thermal diffusivity, $k/C_p\rho$ $\left(ft^2/hr\right)$
r_i	inside tube radius (in.)
r_o	outside tube radius (in.)
L	heated tube length (in.)
D	inside tube diameter (in.)
A	tube heat transfer area, $\frac{2\pi r_o L}{144}$ $\left(ft^2\right)$
q	total heat transfer rate (Btu/hr)
q/A	heat flux at tube wall $\left(Btu/ft^2\ hr\right)$
ΔT	temperature difference between the tube wall at the bottom of the tube and the fluid centerline at the top of the tube (°F)
θ	time for all fluid in the tube to attain saturation temperature (hr)
N_{Nu}	Nusselt Number, $\frac{(q/A)L}{12k\,\Delta T}$
N_{Ra}	Rayleigh Number, $\frac{\beta g \Delta T \left(r_i\right)^3}{\nu\alpha(12)^3}$

N_{Pr}	Prandtl Number, $\frac{C_p \mu}{k}$	
N_{Fo}	Fourier Number $\frac{\alpha\theta(12)^2}{r_i^2}$	
L/D	dimensionless geometry ratio	
Z	correlation parameter, $\frac{(q/A)L}{12\alpha(N_{Pr})^{1/3}}$ (Btu/ft^3)	

I. INTRODUCTION

The phenomena termed geysering can be described as the expulsion, from a vertical tube, of a boiling liquid and its vapor. Many rocket vehicles utilize cryogenic fluid as the propellant. The geyser problem arises in the design of propellant feed systems, which typically use long, large diameter tubes to connect the propellant tank to the engine. Because the propellants are cryogenic, the atmosphere heats the propellant in the feed line during the time period following missile fueling and before launch. If a geyser occurs during this period and the tube is emptied of liquid, the refilling liquid can cause impact loads at the bottom of the tube high enough to seriously damage the vehicle. In addition, if the feed line is damaged, the propellant in the missile tank will drain out creating a safety hazard throughout the launch area.

If sufficient information concerning the factors that produce geysering were available during the initial design of the propellant feed system, the geyser problem could possibly be eliminated by appropriate design. The primary objective of this study was the investigation of the geometrical, thermal, and fluid properties of a system that cause geysering. In addition, several possible methods of geyser suppression were qualitatively investigated.

II. TECHNICAL DISCUSSION

When a long vertical tube containing a reservoir at the top and closed at the bottom is filled with liquid and heated along the tube wall, the heat will be transferred to the liquid surface by means of free convection. This convection process establishes fluid circulation within the tube by which heated fluid rises and cool fluid from the reservoir descends down the tube. A portion of the heat entering at the tube wall will be liberated at the liquid surface in the reservoir by evaporation and the remainder will result in an enthalpy gain in the liquid. This enthalpy gain causes an increase in the fluid bulk temperature.

As the heating process continues, the fluid bulk temperature is increased until the saturation temperature is attained. After the fluid becomes saturated, additional heat input to the liquid results in bubble formation. According to McGrew (Ref 1), the bubbles are formed on the wall and then detach and start to rise in the liquid and begin to coalesce to form a larger single bubble called a Taylor bubble as shown in Fig. 1. The formation of a large bubble results in a pressure reduction below the bubble. Because the liquid below the bubble was at its saturation temperature, the reduction in pressure causes the liquid to flash to vapor thereby forming more bubbles. As new bubbles are formed, the pressure is again reduced flashing more liquid. This self-sustaining reaction occurs quite rapidly and forms vapor at a rate considerably greater than can be removed from the tube. The consequence of the difference in these rates is the explosive expulsion of the liquid from the tube. As the tube is refilled with fluid from the reservoir, the impact of water-hammer force can be as high as 1000 psi for large systems. The potential for structural damage in the refilling process is quite evident.

This report is concerned mainly with the natural convection heat transfer process that brings about the conditions for geysering. Free convection in vertical tubes has been studied analytically by Lighthill (Ref 2), and experimentally by Martin (Ref 3). Lighthill was concerned with the problem of free convection cooling of gas turbine blades by means of drilled passages in the blades and a coolant reservoir in the hub. Martin investigated the same problem and attempted to experimentally verify Lighthill's work. Lighthill's analysis was made on a rigorous basis for both the case of laminar and turbulent flow. He derived dimensionless groups for predicting the heat transfer rate in a vertical tube heated under constant wall temperature conditions. The work of these two investigators represents essentially all of the effort directly applicable to the heat transfer problem in the geyser process; yet, they did not investigate exactly the geyser problem.

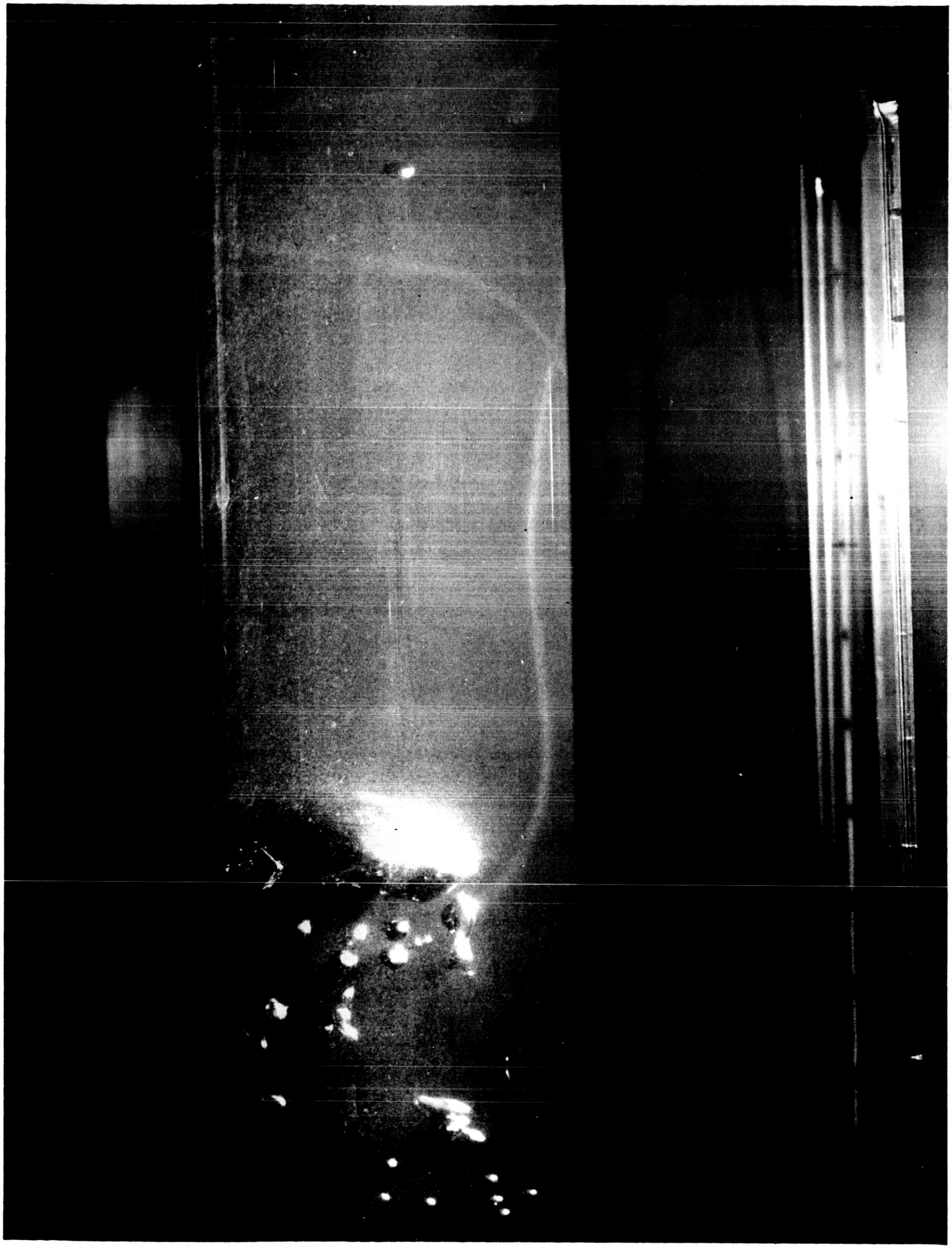

Fig. 1 Taylor Bubble Formation in Water in a 4-in. Pyrex Tube

The first difference was the consideration of constant wall temperature rather than constant heating rate. In a geyser problem, such as encountered in a missile propellant system, the heating rate is constant. The assumption of constant wall temperature may not introduce a significant effect in the case of the cryogenic fluids used in missile systems. This can be explained on the basis of the temperature difference between the boiling surface and the saturated fluid necessary for boiling at a specific heat flux. For liquid hydrogen, this temperature difference is less than 1°F (Ref 4) for nucleate boiling and less than 15°F (Ref 5) for liquid nitrogen and oxygen. Because these differences are so low, the case of constant heating rate may be considered equivalent to constant wall temperature without serious error. A more serious limitation on the Lighthill and Martin work is that they studied only steady-state heat transfer in the liquid phase. In the geyser problem, the temperature buildup is transient and involves a phase change from liquid to vapor. With these limitations in mind, however, the work of both Lighthill and Martin can be used as a guide in understanding the important factors in the natural convection heat transfer process.

Lighthill developed a correlation for the heat transfer rate in laminar flow in terms of the Nusselt number and the quotient of the Rayleigh number and L/r_i ratio. In turbulent flow, he used only the Nusselt and Rayleigh numbers. The Nusselt number for both laminar and turbulent flow as defined by Lighthill is

$$N_{Nu} = \frac{6q}{\pi k L \triangle T}$$

and the Rayleigh number (product of Grashof and Prandtl numbers) defined as

$$N_{Ra} = \frac{\beta g r_i^3 \triangle T}{1728 \nu \alpha}$$

Martin's work agreed quite well with that of Lighthill in the laminar region but his values of Nusselt number were lower than Lighthill predicted for the turbulent region.

The work discussed previously can probably be used to obtain heat transfer coefficients for natural convection in vertical tubes; but it does not provide quantitative answers to the geyser problem. The objective of the present study was to gain an understanding of geysering, in terms of system geometry, heating rate, and fluid properties, sufficient to predict which combinations of these factors produce geysering.

Using the work of Lighthill and Martin as a starting point, an experimental study was conducted to obtain a method of predicting geysering.

III. DESCRIPTION OF EXPERIMENTAL PROGRAM

The experimental program was conducted at the Experimental Test Laboratory of the Martin-Marietta Corporation, Denver Division. The program consisted of two phases: geyser tests and geyser suppression tests. Each of these phases is described in detail in the following sections.

A. PHASE I - GEYSER TESTS

The geyser tests consisted of heating a vertical tube filled with a test fluid to determine if the tube would or would not geyser. The test fluids used were water, liquid nitrogen, liquid hydrogen, and Freon 113. Various tubes were tested ranging from 4-in. to 13-in. diameter. Length to diameter ratios were varied between 1.5 and 30, and the heat flux range studied was between 50 and 2100 Btu/ft^2-hr.

The test apparatus used in this phase can be divided into 4 major categories: 1) geyser tube; 2) heating system; 3) instrumentation system; and 4) photographic system.

1. Geyser Tube

The general geyser tube configuration used in all geyser tests is shown in Fig. 2. Table 1 contains the numerical values for the dimensions shown in Fig. 2 for the various tubes used in the study as well as the material of construction and the test fluids used in each tube. The reservoir used with Tubes A and B for the water and Freon tests was fitted with a conical baffle (Fig. 3) to retain the test fluid in the reservoir during a geyser. All of the reservoirs used were externally insulated with a 1-in. layer of polyurethane foam to minimize heat transfer either from or to the fluid in the reservoir. Also, a 2-in. polyurethane foam cover was placed on the reservoir to prevent excessive heat loss during a geyser test.

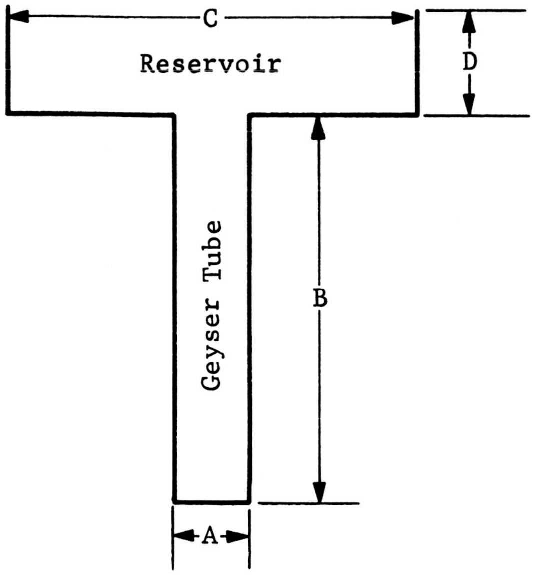

Fig. 2 Geyser Tube Configuration

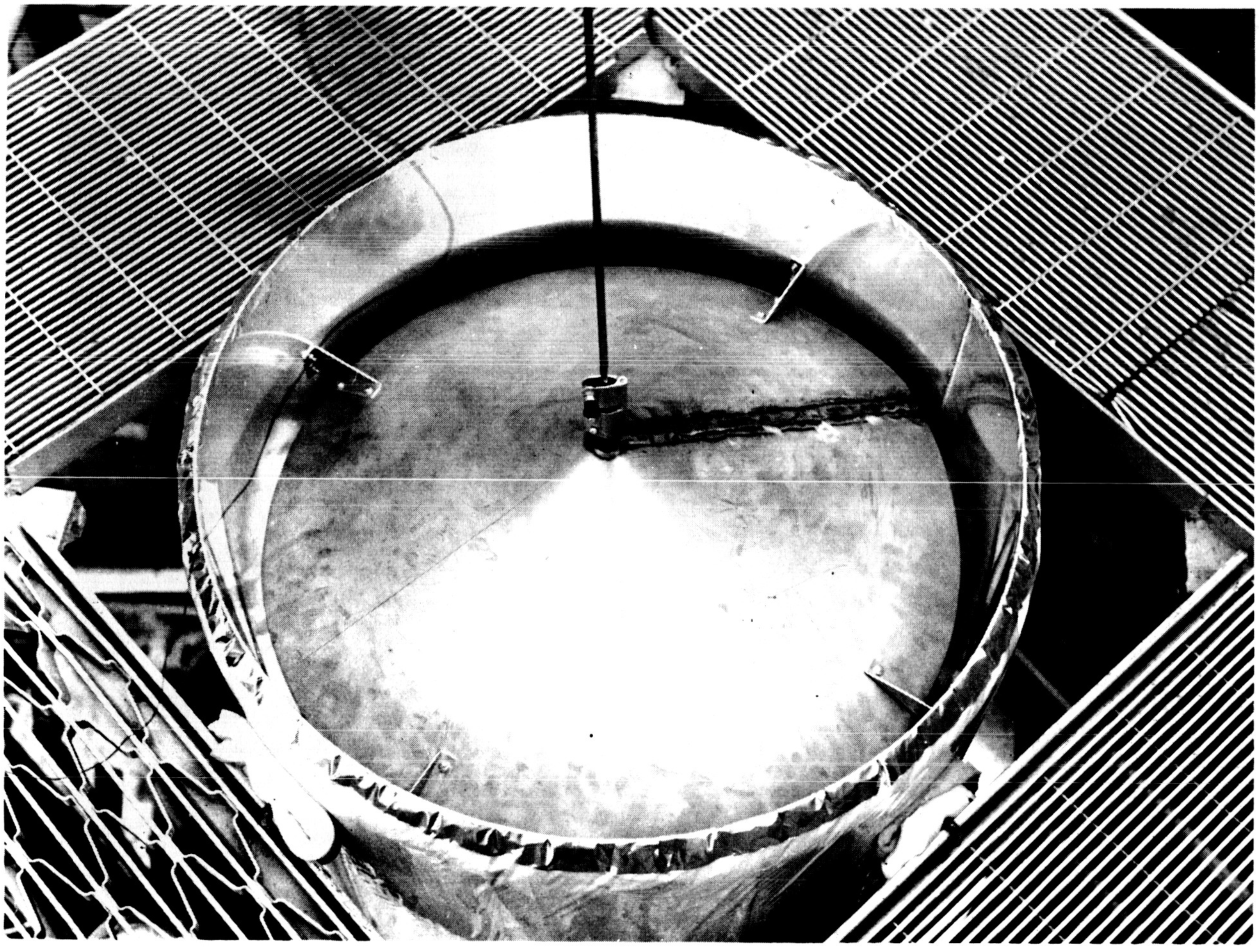

Fig. 3 Conical Baffle in Reservoir

Table 1 Geyser Tube Description

Tube Designation	A Tube Diameter (in.)		B Tube Length Tested (ft)	C Reservoir Diameter (in.)	D Resivoir Height (in.)	Tube Material	Test Fluid
	ID	OD					
A	4.22	4.75	2 thru 9	30	24	Pyrex	H_2O
B	4.00	4.50	2 thru 10	30	24	Aluminum	H_2O, Freon 113, LN_2, LH_2
C	5.75	6.00	8	30	12	Aluminum	LN_2
D	7.75	8.00	9, 12, 14	30	12	Aluminum	H_2O, LN_2
E	13.00	13.50	28.3	40	10	Aluminum	LN_2

All of the reservoirs were constructed of aluminum. The aluminum tubes were welded directly to the reservoir; the pyrex tube was connected to the reservoir by means of a rubber union. The union was clamped to the pyrex tube and to a flange welded to the reservoir. The closure at the bottom of the pyrex tube was fashioned in a similar manner. A rubber union connected the glass tube to a piece of aluminum pipe containing a flange that made the closure. Inside this section of pipe, a rubber balloon was installed as a shock absorber to prevent damage to the tube during refill following a geyser.

Pressure taps and fill connections were installed at the bottom of each geyser tube for monitoring the hydrostatic pressure during geysering and for filling the tube.

2. Heating System

The heating system used for Tubes A and B with water and Freon consisted of infrared heating lamps. Figure 4 shows geyser Tube A with the heating system installed in the test cell. These lamps (General Electric T-3 heating lamps) were approximately 12-in. long and were capable of producing 1000 watts when operated on 220 volts. The system contained 11 rows (covering approximately 12 ft of tube length) with 8 lamps in each row. These 8 lamps were equally spaced around the geyser tube periphery with the lamp center 3 in. from the tube wall. Aluminum reflectors were installed behind the lamps to direct the radiation and to provide uniform heating on the tube surface. The voltage across the lamps was controlled by means of a 220-volt 3-phase variac. The power rating of this variac was 45 amps at 220 vac. Each of the rows was wired through a toggle switch for individual control. This arrangement permitted operation of one row, all eleven, or any combination at one time by energizing the desired number of rows from the top of the tube. The fluid below the last energized row was essentially unaffected by the heating lamps.

In order to simulate a missile line, the water must be heated by convection from the hot tube wall. Because the heating was by radiation, it was necessary to increase the absorptivity of the pyrex tube from a value of about 0.60 to near 1.0 to prevent direct heating of the water by the radiant energy. The higher absorptivity was achieved by painting the pyrex tube with a solution of carbon black and lacquer. The lacquer evaporated leaving the carbon black on the surface thereby providing the desired absorptivity.

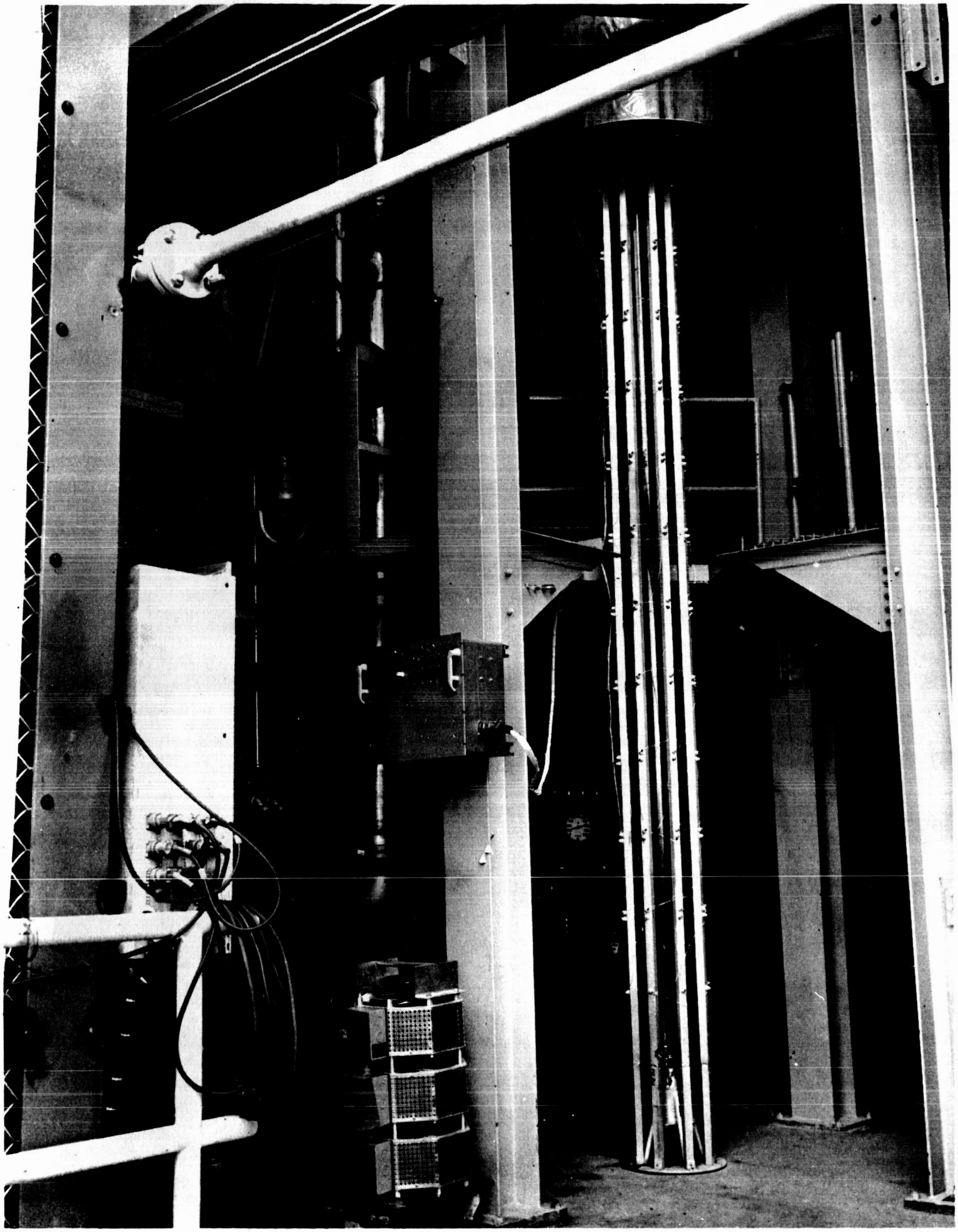

Fig. 4 Geyser Tube A Installed in Test Cell

The heating system was calibrated by filling the tube with water to a level 3 in. above the top row of lamps and applying a constant power to the top row of lamps. The water level was measured by connecting a water manometer to the pyrex tube. Both the water temperature and the outside tube surface temperature were measured with thermocouples, while the water was allowed to boil until the water level decreased to the top of the energized row of lamps. Using the heat of vaporization of water at the measured temperature and the time for the water level to fall 3 in., a heat flux was calculated. The amount of heat being conducted by the water below the top row of lamps was calculated to be approximately 1/4% of the calculated wall heat flux. This procedure was repeated several times at various voltage settings across the lamps, thus providing a calibration of heat flux as a function of power setting. The calibration for the top row was then assumed to be valid over the entire tube length because geysering precluded the use of this method over the full tube length.

Because both liquid nitrogen and liquid hydrogen are cryogenic fluids, an external heating system was not required for the tests with these fluids. Instead, the heat flux was controlled by insulating the geyser tube with predetermined thicknesses of polyurethane foam insulation. The insulation thicknesses used for the liquid nitrogen tests were 1-, 1/2-, and 1/4-in., and no insulation. The thicknesses used in the liquid hydrogen tests were 7-, 4-, and 1/4-in. Because the normal boiling point of liquid hydrogen (-423°F) is below the condensing point of air, it was necessary to provide a helium gas atmosphere around the foam insulation in the hydrogen tests to prevent the condensation of air in the insulation. If this precaution had not been taken, air condensation in the foam would have considerably reduced the effect of the insulation and made it extremely difficult to determine the heat transfer rate to the geyser tube.

The heat flux for the foam insulated tubes was calculated using the one dimension, steady-state conduction equation in cylindrical coordinates, and a measured temperature difference across the foam obtained by using copper-constantan thermocouples. The foam insulation thermal conductivity used in the heat flux calculations for the liquid nitrogen tests was obtained from the work of Haskins and Hertz (Ref 6). For the liquid hydrogen tests, the heat flux was calculated using the thermal conductivity of helium gas from Scott (Ref 7), because the thermal conductivity of the foam insulation is almost completely dependent upon the interstitial gas. During the liquid hydrogen nongeyser tests, boiloff rates were obtained and converted to tube wall heat fluxes. These fluxes were compared with the predicted heat fluxes based on helium gas thermal conductivity. Good agreement was attained, thereby verifying the method of using helium gas thermal conductivity for heat flux calculation. The heat flux for all the uninsulated liquid nitrogen tests could not be readily calculated because of small quantities of air condensing on the tube. The work of Ruccia and Mohr (Ref 8) on heat transfer to uninsulated liquid oxygen tanks was used as a basis for estimating the heat transfer to the uninsulated liquid nitrogen tubes. A value of 700 Btu/ft^2-hr was selected as being a close approximation of the actual heat flux.

Figure 5 shows geyser Tube B uninsulated, installed in the test cell during a liquid nitrogen test. Figure 6 shows geyser Tube C installed in the test cell. Figure 7 shows geyser Tube D during a liquid nitrogen geyser. Figure 8 shows geyser Tube B, with 7 in. of insulation, during a liquid hydrogen geyser test. Figure 9 shows geyser Tube E installed in the test cell.

When liquid nitrogen was used as the test fluid, heating of the liquid commenced immediately upon the start of filling. Because of this immediate heating, difficulties were encountered in trying to distinguish between geysering and fill transients. To alleviate this problem, gaseous helium was injected at the bottom of the tube during liquid nitrogen filling to subcool the nitrogen sufficiently to obtain a definable and repeatible test starting condition. Helium injection was continued after the tube was filled until a quiescent liquid surface was attained in the reservoir. The helium was then shut off and the tube allowed to geyser. Similar problems were not experienced with liquid hydrogen.

The heating system used on geyser Tube D for the water tests consisted of a series of electric blanket heaters. These heaters, each consisting of a blanket of resistance wire, were 12 in. wide and 25 in. long. They were wrapped around the tube and covered with a 1-in. layer of polyurethane foam insulation to minimize losses to the surroundings. Figure 10 shows geyser Tube D with part of the blanket heaters and foam insulation installed. The heaters were powered by means of the 220-volt variac previously described. The heat flux was determined by measuring the power input to the heaters, and subtracting the calculated losses through the foam insulation. The foam losses were calculated using the steady-state conduction equation. Again the temperature difference across the foam was determined from thermocouple measurements.

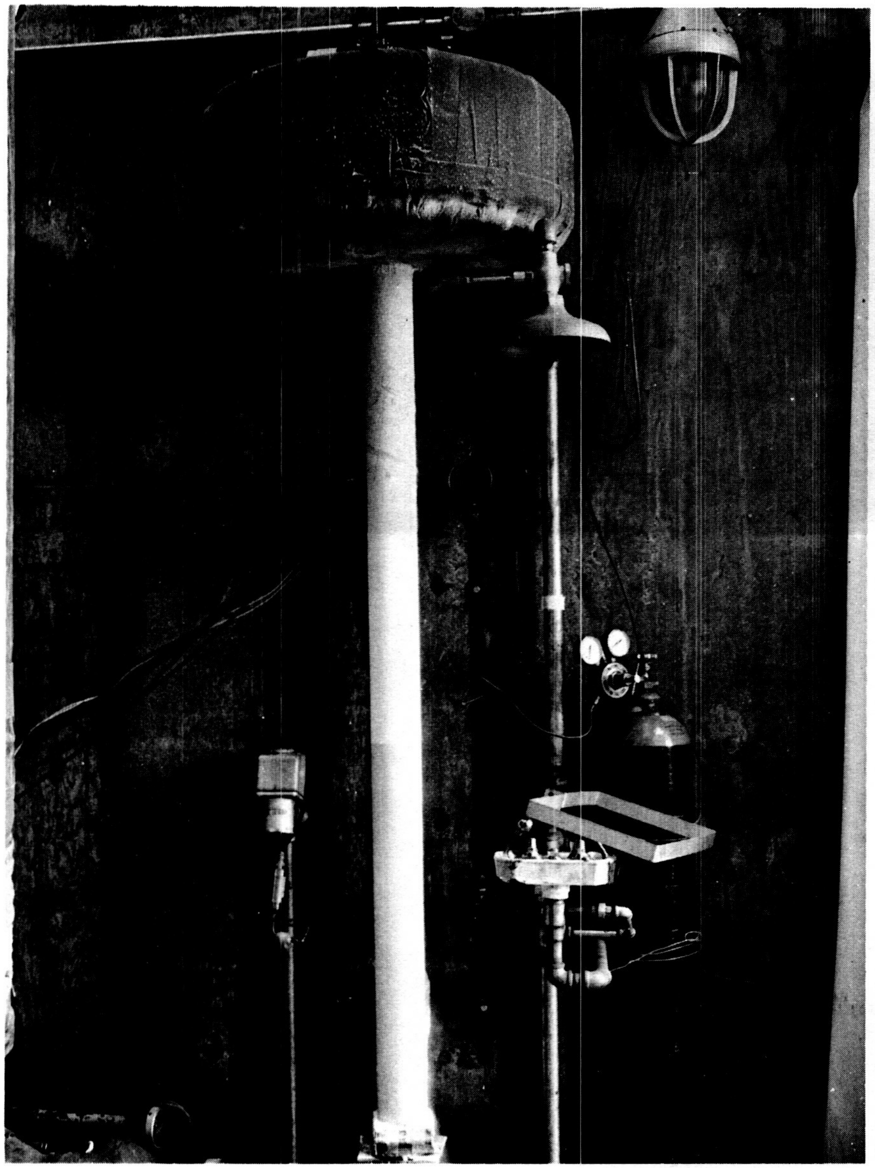

Fig. 5 Geyser Tube B Installed in Test Cell

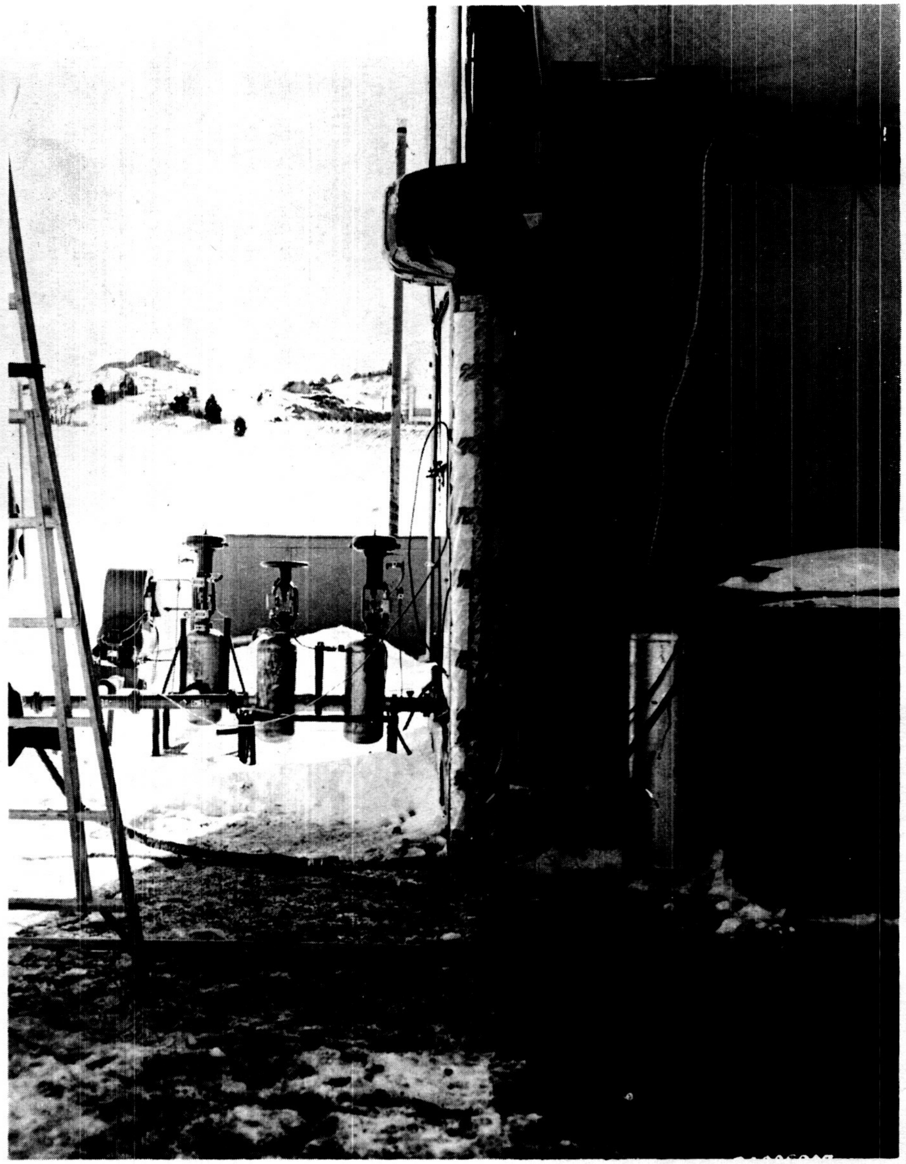

Fig. 6 Geyser Tube C Installed in Test Cell

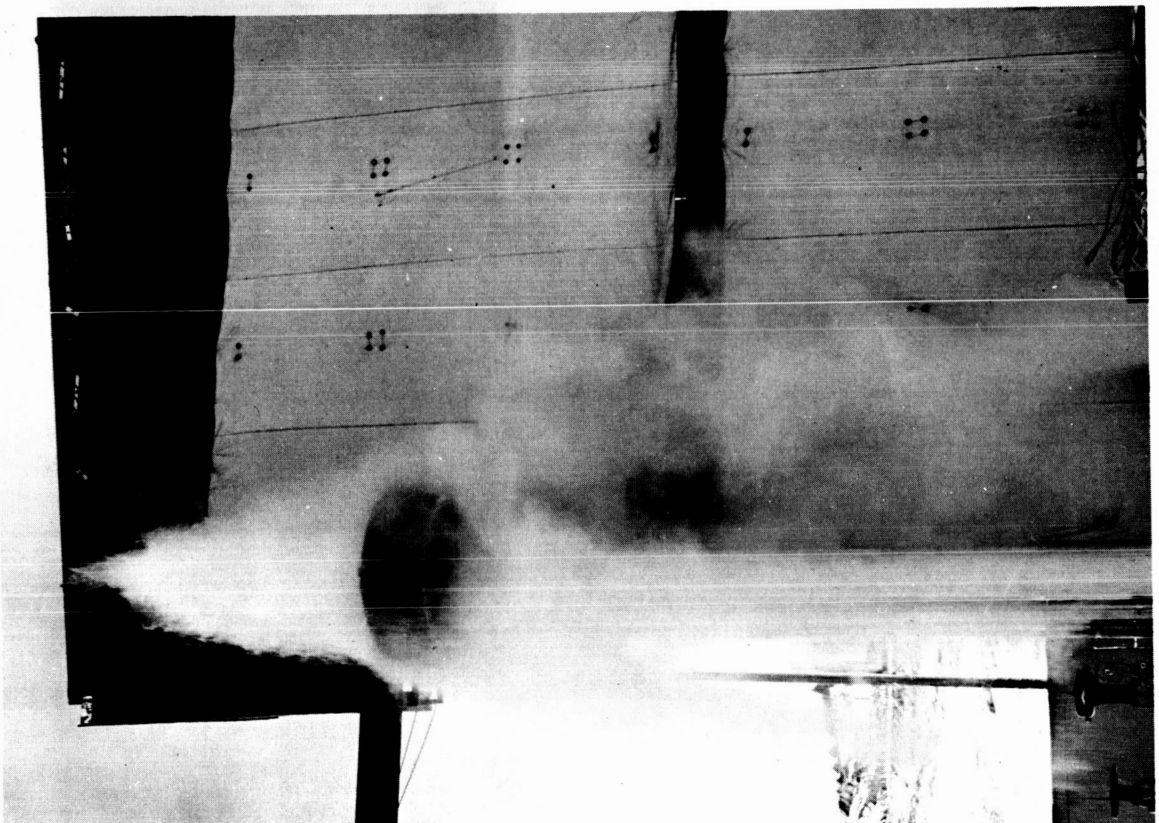

Fig. 7 Geyser Tube D During a Liquid Nitrogen Geyser Test

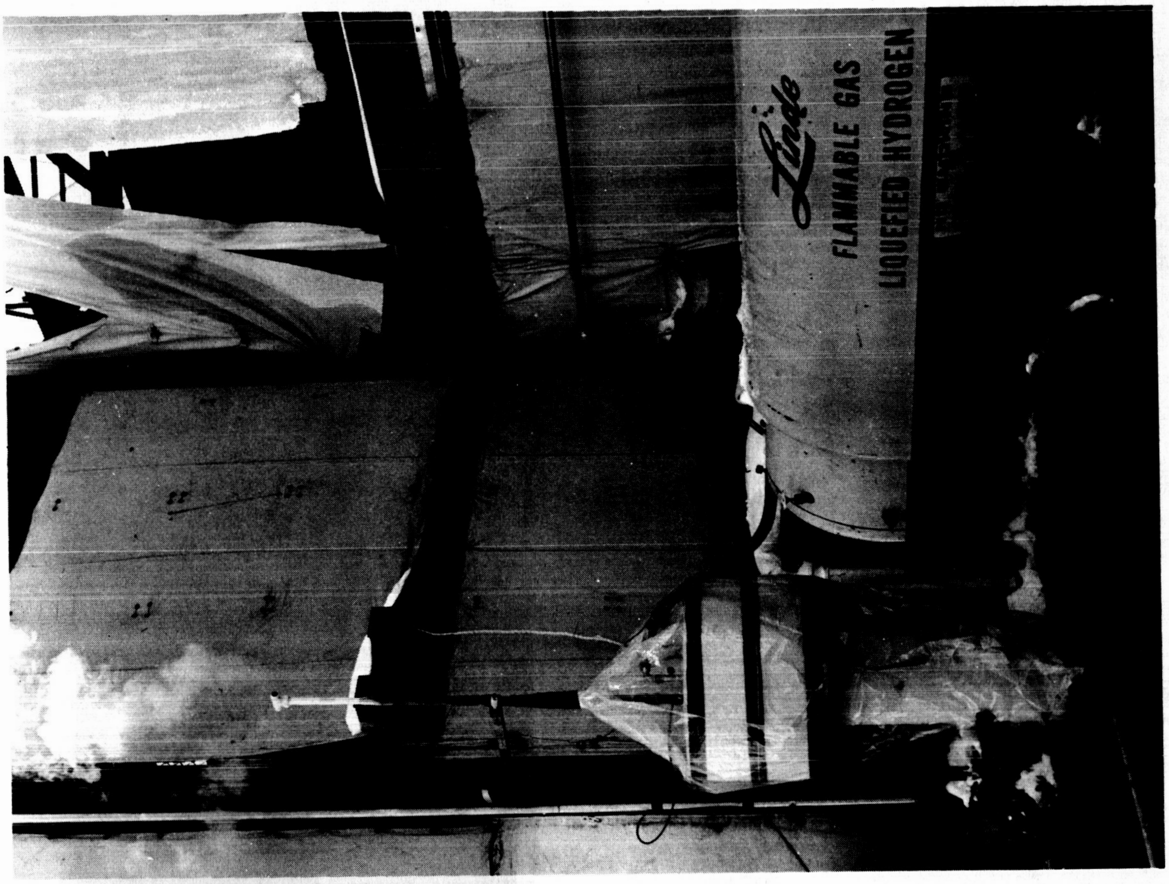

Fig. 8 Geyser Tube B During a Liquid Hydrogen Geyser Test

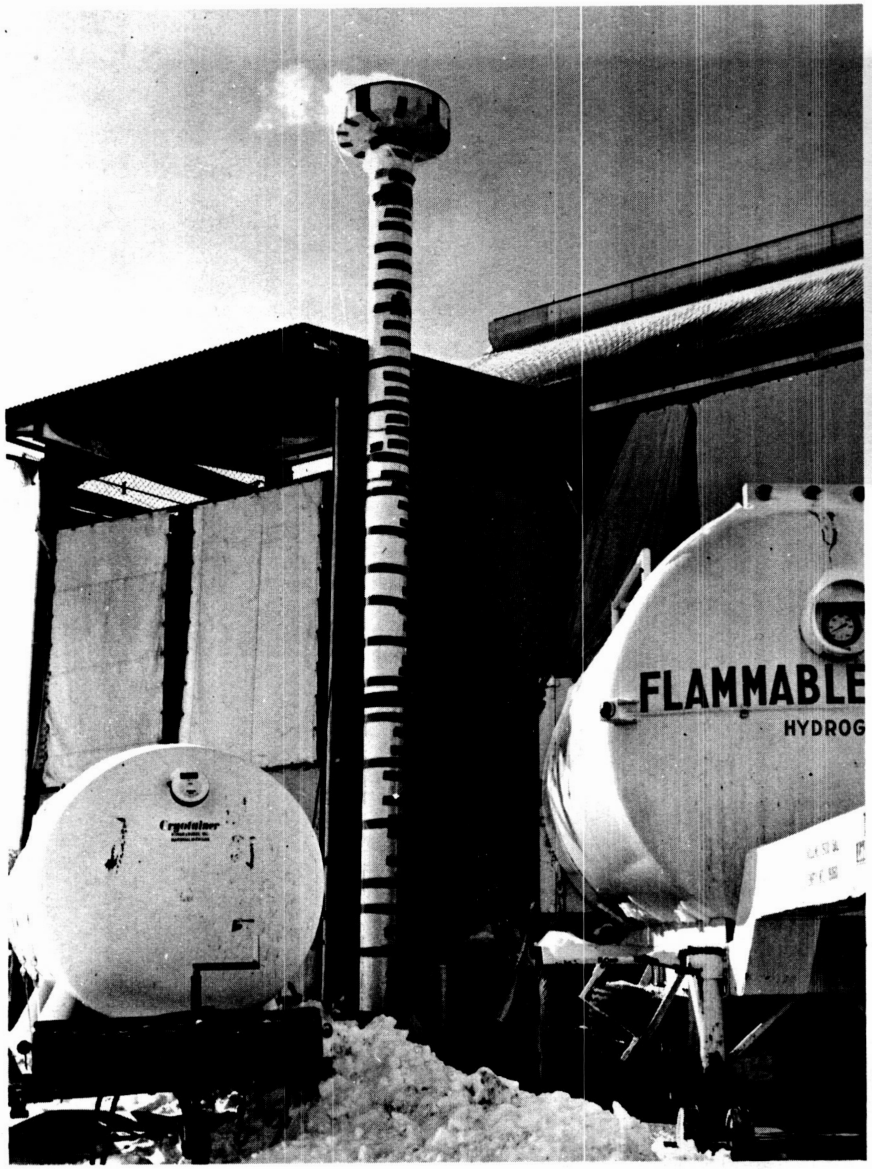

Fig. 9 Geyser Tube E During a Liquid Nitrogen Test

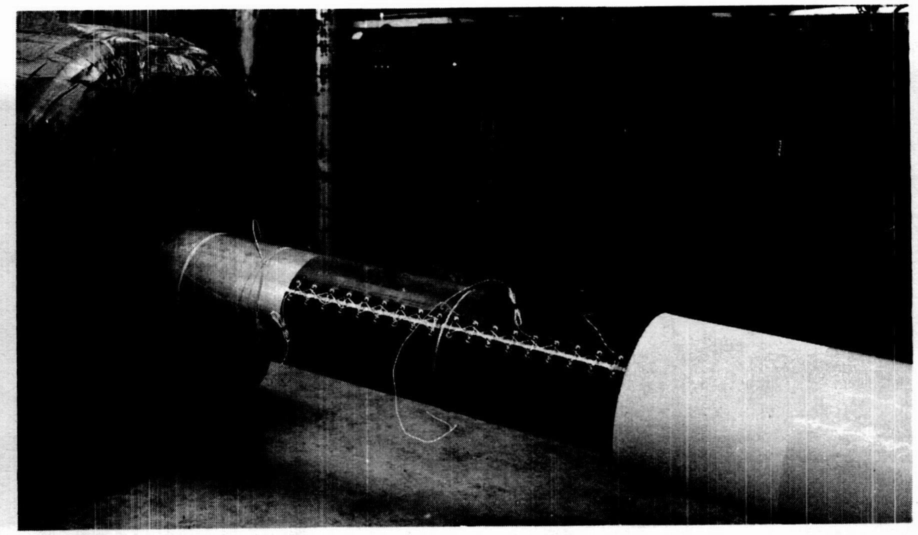

Fig. 10 Geyser Tube D Installed in Test Cell for Water Geyser Tests

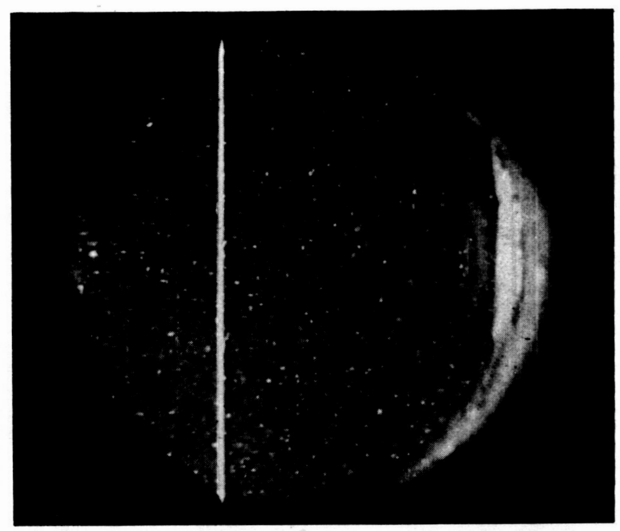

Fig. 11 Typical Photograph of "Eccospheres" in Water

3. Instrumentation

The instrumentation used in the geyser test phase consisted of temperature and pressure measurements. Tube wall and insulation surface temperatures were measured in all tests. Fluid temperatures were measured only on the tests with geyser Tubes A and B. Fluid temperatures were not measured during the liquid hydrogen tests.

In the water and Freon tests, the fluid temperatures were measured by means of a movable thermocouple probe installed along the tube centerline. The thermocouples were installed at the bottom of the probe, and the probe was raised or lowered to measure the temperature at any desired level in the tube. For the liquid nitrogen tests, a fixed probe containing thermistors mounted at 1-ft intervals was used.

The static pressure at the base of the geyser tube was measured by means of a strain gage pressure transducer. This pressure was recorded during all tests for the purpose of identifying geysering in the tube.

a. Thermocouples

The fluid and tube wall temperatures for all the water and Freon tests, as well as the foam insulation temperatures, were measured with copper-constantan thermocouples. The thermocouples used were made from standard 1 1/2%, 30 ga, Teflon insulated thermocouple wire. All of the measurements were referenced to a common ice water bath. The readout equipment was either a recording oscillograph or a recording self-balancing potentiometer, depending on the test requirements. The calibration consisted of inputting known millivoltages into the measuring circuit, according to the National Bureau of Standards tables, by means of a hand balancing potentiometer. The accuracy of these measurements was ±2°F.

b. Thermistors

The liquid nitrogen fluid and tube wall temperatures were measured by means of thermistors. The thermistors used were Keystone Carbon Model L0904. They were installed in a resistance bridge circuit and recorded on a recording oscillograph. They were individually calibrated in a special calibration cryostat using a vapor pressure calibration technique. The accuracy of these measurements was ±0.25°F.

c. Pressure

A Statham strain gage pressure transducer was utilized for all pressure measurements in the test program. The measurement was recorded either on a self-balancing potentiometer or oscillograph depending on the test conditions. Calibration was achieved by means of a dead weight calibration technique.

4. Photographic System

Because the fluid circulation and boundary layer growth is a major factor in geysering, a photographic technique was developed in an attempt to obtain this type of data. The technique was developed for use on the pyrex geyser tube with water as the test fluid. The technique consisted of taking motion pictures of the movement of small glass spheres placed in the water. The glass spheres used were Eccospheres made by Emerson and Cuming, Inc and ranged from 30 to 300 microns in diameter. The density varied with sphere diameter, therefore some of the spheres either floated on the water surface or sank to the bottom while the remainder were suspended in the water and their motion was that of the water.

To illuminate and photograph the spheres in the pyrex tube, a quarter-inch strip was left unpainted along the entire tube length for illumination and the paint was scraped from the tube in a 2-inch circle to provide camera ports. Light from a high intensity flood lamp was admitted through the unpainted strip providing a plane of light through the center of the tube. A 16 mm movie camera (24 fr/s) was placed normal to the plane of light at a camera port to record the motion of the spheres. These ports were scraped as required and repainted after filming to minimize direct heating of the water.

The heating lamps emitted an orange light so it was necessary to shield this light from the movie camera. To do this, a 2-in. aluminum tube, 12 in. long, was fixed to the camera. This tube provided a complete shield between the camera and geyser tube so that the only light available to expose the movie film was that coming through the 1/4-in. strip.

The technique proved to be quite successful. Approximately 500-ft of film was exposed providing pictures of fluid motion as a function of both time and water temperature at various locations along the tube length. Figure 11 is an enlargement of one frame of the movies to show the type of pictures obtained. The white line is a guidewire for the thermocouple probe and the tube wall is on the right.

All of the films were analyzed in an attempt to define flow patterns and boundary layer development that would assist in describing geysering. Rather than the expected orderly flow, the movies showed great turbulence and random fluid movement up and down the tube. There was no discernible boundary layer development in any of the films.

Because of the random nature of the flow coupled with the turbulence, the data could not be interpreted. Therefore, the photographic experiments were terminated.

5. Geyser Test Results

A summary of the geyser tests conducted during the experimental program including the test conditions is contained in Table 2. The majority of the effort was expended on tests with the 4-in. tubes and the four test fluids (water, liquid nitrogen, liquid hydrogen, and Freon 113).

The initial attempt to attain a correlation that would distinguish between geyser and nongeyser conditions as a function of heat flux, tube geometry, and fluid properties was based on the work by Lighthill (Ref 2) and Martin (Ref 3). The data taken at the onset of geysering from the tests with geyser Tubes A and B, and all three test fluids, were plotted in the form of the Nusselt number versus the Rayleigh number.

The fluid properties were evaluated at the arithmetic mean temperature between the top fluid centerline and bottom inside wall temperatures. The inside wall temperature could not be measured but was determined. In the case of the aluminum tube, the outside wall temperature was measured and assumed to be equal to the inside wall temperature. Because of the high thermal conductivity of aluminum, this assumption does not introduce a significant error. This could not be done for the pyrex tube. The inside wall temperature was determined by calculating the temperature drop across the tube wall and subtracting it from the measured outside wall temperature.

Table 2 Summary of Geyser Tests Conducted

Test No.	Geyser Tube	Test Fluid	q/A (Btu/ft^2-hr)	Heated Length (ft)	Geyser	L/D	L/D ($D^{-0.68}$) (in.$^{-0.68}$)	Z (Btu/ft^3)
1	A	Water	410	3	No	8.55	3.22	1.55 x 10^5
2				4	No	11.4	5.35	2.07
3				5	Yes	14.2	5.34	2.58
4				6	Yes	17.1	6.43	3.10
5				7	Yes	19.9	7.50	3.62
6				8	Yes	22.8	8.58	4.14
7				9	Yes	25.6	9.63	4.75
8			365	4	No	11.4	4.30	1.84
9				5	Yes	14.2	5.35	2.31
10				6	Yes	17.1	6.43	2.76
11				7	Yes	19.9	7.50	3.23
12				8	Yes	22.8	8.58	3.68
13				9	Yes	25.6	9.63	4.14
14			315	5	Yes	14.2	5.35	1.89
15				6	Yes	17.1	6.43	2.38
16				7	Yes	19.9	7.50	2.78
17				8	Yes	22.8	8.58	3.16
18				9	Yes	25.6	9.63	3.58
19			265	5	Yes	14.2	5.35	1.66
20				6	Yes	17.1	6.43	2.00
21				7	Yes	19.9	7.50	2.34
22				8	Yes	22.8	8.58	2.68
23				9	Yes	25.6	9.63	3.00
24			215	3	No	8.55	3.22	0.813
25				4	No	11.4	4.30	1.09
26			120	8	Yes	22.8	8.58	1.21
27	B		410	2	No	6.0	2.34	1.03
28			315	2	No	6.0	2.34	0.795
29				3	No	9.0	3.50	1.19
30				4	No	12.0	4.67	1.59
31			215	2	No	6.0	2.34	0.542
32		Freon	620	2	No	6.0	2.34	3.79
33				4	Yes	12.0	4.67	7.90
34				6	Yes	18.0	7.00	11.30
35				8	Yes	24.0	9.35	15.20
36			530	2	No	6.0	2.34	3.24
37				4	Yes	12.0	4.67	6.50
38				6	Yes	18.0	7.00	9.76
39				8	Yes	24.0	9.35	13.00
40				10	Yes	30.0	11.70	16.30
41			420	2	No	6.0	2.34	2.56
42				4	Yes	12.0	4.67	5.15
43				6	Yes	18.0	7.00	7.73
44	B	Freon	420	8	Yes	24.0	9.35	10.30
45				10	Yes	30.0	11.70	12.80
46			380	2	No	6.0	2.34	2.14
47				4	Yes	12.0	4.67	4.30
48				6	Yes	18.0	7.00	6.45
49				8	Yes	24.0	9.35	8.58
50				10	Yes	30.0	11.70	10.70
51			275	2	No	6.0	2.34	1.68
52				4	Yes	12.0	4.67	3.35
53				6	Yes	18.0	7.00	5.04
54				8	Yes	24.0	9.35	6.72
55				10	Yes	30.0	11.70	8.42
56			206	2	No	6.0	2.34	1.25
57				4	No	12.0	4.67	2.51

Table 2 (concl)

Test No.	Geyser Tube	Test Fluid	q/A (Btu/ft^2 hr)	Heated Length (ft)	Geyser	L/D	L/D ($D^{-0.88}$) ($in.^{-0.68}$)	Z (Btu/ft^3)
58				6	Yes	18.0	7.00	3.76
59				8	Yes	24.0	9.35	5.01
60				10	Yes	30.0	11.70	6.26
61			145	2	No	6.0	2.34	0.89
62				4	No	12.0	4.67	1.78
63				6	Yes	18.0	7.00	2.67
64				8	Yes	24.0	9.35	3.56
65				10	Yes	30.0	11.70	4.45
66		LN_2	700	1.5	No	4.5	1.75	2.46
67				2.5	No	7.5	2.92	4.11
68				3.5	No	10.5	4.09	5.75
69				4.5	Yes	13.5	5.25	7.40
70				5.5	Yes	16.5	6.42	9.05
71				6.5	Yes	19.5	7.60	10.70
72			85	1.5	No	4.5	1.75	0.294
73			80	2.5	No	7.5	2.92	0.470
74			81	3.5	No	10.5	4.09	0.687
75			81	4.5	Yes	13.5	5.25	0.855
76			82	5.5	Yes	15.5	6.42	1.06
77			87	6.5	Yes	19.5	7.60	1.33
78	B	LN_2	61	1.5	No	4.5	1.75	0.215
79			58	2.5	No	7.5	2.92	0.348
80			61	3.5	No	10.5	4.09	0.503
81			60	4.5	Yes	13.5	5.25	0.635
82			61	5.5	Yes	16.5	6.42	0.790
83			62	6.5	Yes	19.5	7.60	0.948
84			43	1.5	No	4.5	1.75	0.152
85			40	2.5	No	7.5	2.92	0.235
86			42	3.5	No	10.5	4.09	0.346
87			41	4.5	No	13.5	5.25	0.435
88			43	5.5	Yes	16.5	6.42	0.557
89			42	6.5	Yes	19.5	7.60	0.641
90	C		34	8	Yes	16.7	5.08	1.57
91			49	8	Yes	16.7	5.08	0.920
92			28	8	No	16.7	5.08	0.526
93	D	Water	756	9	No	13.9	3.45	8.57
94			350	9	No	13.9	3.45	6.25
95			1960	12	Yes	18.6	4.62	30.00
96			1600	12	Yes	18.6	4.62	24.30
97			530	12	No	18.6	4.62	8.00
98			338	12	No	18.6	4.62	5.10
99		LN_2	700	9	No	13.9	3.45	14.80
100			83	9	No	13.9	3.45	1.75
101			700	12	Yes	18.6	4.62	19.60
102			182	12	No	18.6	4.62	4.28
103			51	12	No	18.6	4.62	1.44
104			700	14	Yes	21.6	5.36	23.00
105			149	14	Yes	21.6	5.36	4.89
106			85	14	Yes	21.6	5.36	2.80
107			48	14	Yes	21.6	5.36	1.66
108	B	LH_2	770	3.42	No	10.3	4.00	3.74
109			169	3.42	No	10.3	4.00	0.819
110			92	3.42	No	10.3	4.00	0.443
111			770	5	Yes	15.0	5.83	5.45
112			92	5	Yes	15.0	5.83	0.650
113	E	LN_2	44	28.3	Yes	26.2	4.60	2.92
114			14.7	28.3	No	26.2	4.60	0.978

The data agreed with that of Lighthill and Martin, but did not present a means of distinguishing between geysering and nongeysering conditions. It should be noted that when the Nusselt number was plotted as a function of the Rayleigh number and the results compared with the Lighthill and Martin work, a transient and a steady-state condition were being compared. The geyser process is a transient condition from the start of liquid heat up to the expulsion. Lighthill and Martin were concerned only with the maximum steady-state heat transfer rate from the tube.

Since the geyser process is strongly time dependent, and the attainment of liquid saturation is a prerequisite for geysering, the time required for all the fluid in the tube to attain saturation seemed to be a significant variable upon which to attempt a correlation. This time parameter was included in the correlation through the use of the Fourier number (N_{FO}). The Fourier number (Ref 9) is defined as

$$N_{FO} = \frac{(144)k\theta}{C_p \rho r^2}$$

Time zero was taken at the time the fluid in the tube was at a uniform temperature equal to the saturation temperature at the top of the tube.

A correlation of the test data from geyser Tubes A and B was attempted by plotting the Nusselt number as a function of the Rayleigh-Fourier number product. This attempt failed to yield a desirable correlation.

These data were then cross-plotted and adjusted by means of a series of trial and error approaches until a plot of the tube geometry ratio L/D (the heated tube length divided by the tube inside diameter) as a function of a parameter Z was attained. The parameter Z is defined as

$$Z = \frac{(q/A)L}{12\alpha\left(N_{pr}\right)^{1/3}}$$

This method of plotting yielded the desired separation between the geyser and nongeyser regimes for the data obtained from geyser Tubes A and B.

Data from tests conducted with geyser Tubes C, D and E were plotted to verify the correlation for other diameters. The results showed that a correlation of L/D versus Z was not sufficient to describe geysering as a function of tube diameter. Analyzing the data from Tubes C, D, and E showed that replacing the term L/D by $(L/D)(D^{-0.68})$ resulted in a geyser-nongeyser correlation valid for all tube diameters and fluid properties. This final correlation is presented in Fig. 12.

The fluid properties contained in the parameter Z were evaluated at the temperature corresponding to fluid saturation at standard atmospheric pressure (14.7 psia). This condition was chosen as a convenient standard for practical use and is justified on the basis that the exact same correlation was attained when the fluid properties were evaluated at saturation temperature corresponding to both 25 and 50 psia.

In the tests conducted in this study, the pressure at the top of the geyser tube was atmospheric (12 psia). In the case of an actual missile system the pressure at the top of the propellant feedline will be considerably above atmospheric (as great as 2.5 atmos), depending on the depth of liquid in the missile propellant tank and the ullage pressure. Griffith (Ref 10) has shown that the tendency of a tube to geyser is essentially independent of the pressure at the top of the tube. In his investigation, Griffith conducted geyser tests on various tubes and fluids with the pressure at the top of the tube ranging from 1 to 2.5 atmospheres. His conclusions were that while increasing the pressure retards the bubble formation rate, and consequently the geyser frequency, a geyser still occurred. Since this investigation is concerned only with determining if a tube will or will not geyser, and not the geyser frequency, this correlation should adequately describe the combinations of fluid properties, heating rates, and system geometry that will produce geysering.

There is no theoretical basis for the correlation shown in Fig. 12. The justification for this method of data presentation lies in the fact that it adequately describes the conditions that produce geysering. Figure 12 satisfies the objectives of this study in that by means of this correlation, geysering can be predicted.

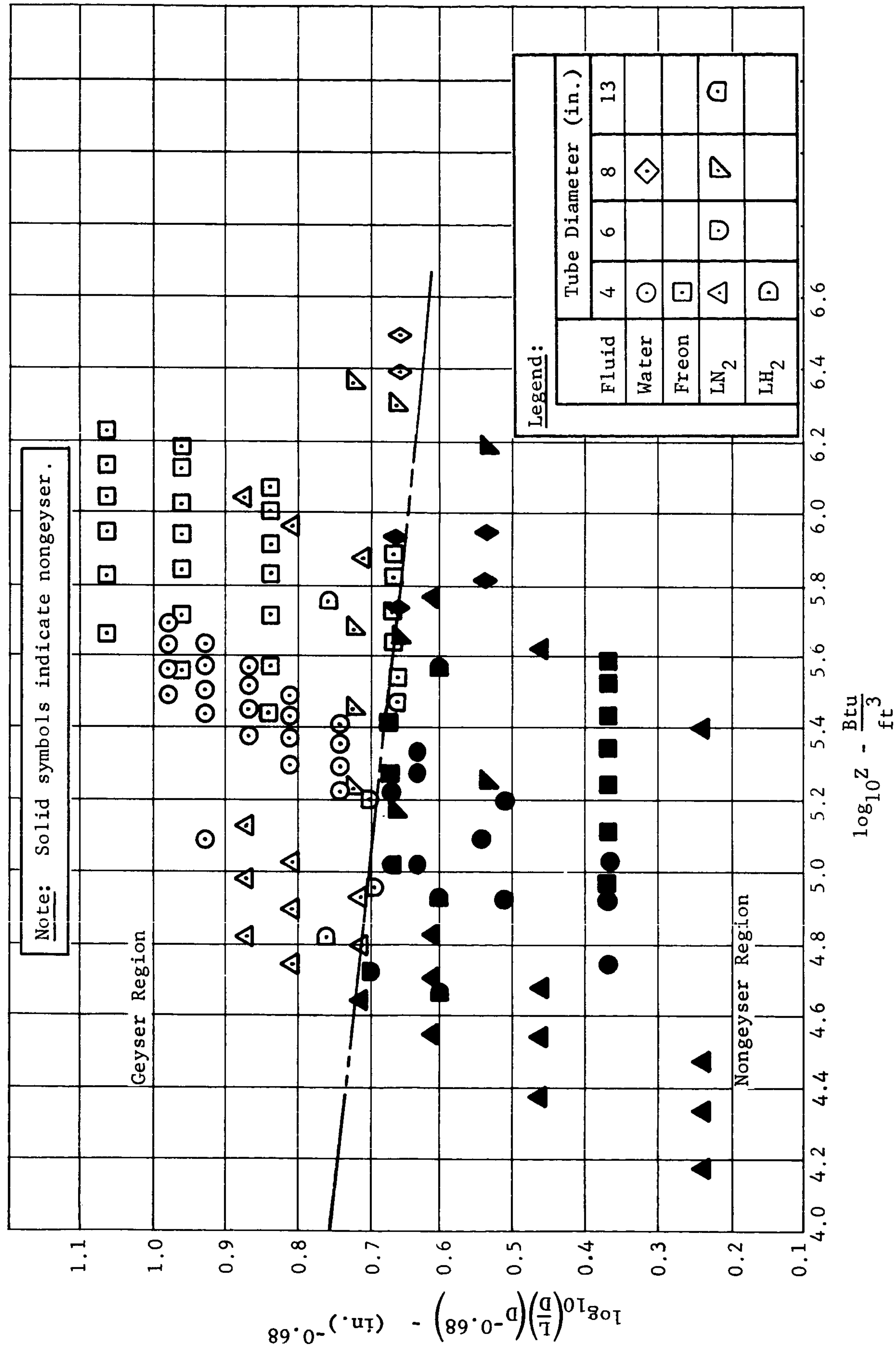

Fig. 12 Geyser-Nongeyser Correlation

The importance of this correlation is its value as a design tool. For instance, a propellant feedline for a missile can be designed in the normal manner and then the design checked with this correlation to determine if geysering will occur. If the line will geyser, it may then be possible to prevent geysering by a modification in the design.

At the beginning of the experimental program, it was anticipated that the temperature profiles in the tube would be helpful in predicting geysering. Like the photographic data, difficulties arose in understanding the significance of the temperature profiles and consequently these data were not used in the geyser-nongeyser correlation.

Figures 13 thru 16 show typical fluid time-temperature profiles along the geyser tube centerline during a geyser period. All the time-temperature data obtained are presented in Section Report 0560-64-15 "Data Report, Fluid Heatup Rates during Geyser Tests."

The test numbers identified on the figures refer to the numbers in Table 2. Time zero was taken at the completion of a geyser and the data are plotted until the time of the next geyser. The numbers alongside each curve refer to specific locations along the centerline. Number 1 is located one foot from the bottom of the heated length and the succeeding numbers are located at one-foot intervals up the tube.

B. PHASE II - GEYSER SUPPRESSION TESTS

Following the development of the geyser-nongeyser correlation approximately 1 1/2 months remained in the program. This time was used in briefly examining some possible geyser suppression methods. The objective of these tests was to obtain a qualitative evaluation of the feasibility of these methods.

1. Test Description

Four possible methods of geyser suppression were tested:

1) Heater at the base of the geyser tube;

2) Horizontal tube at the base of the geyser tube;

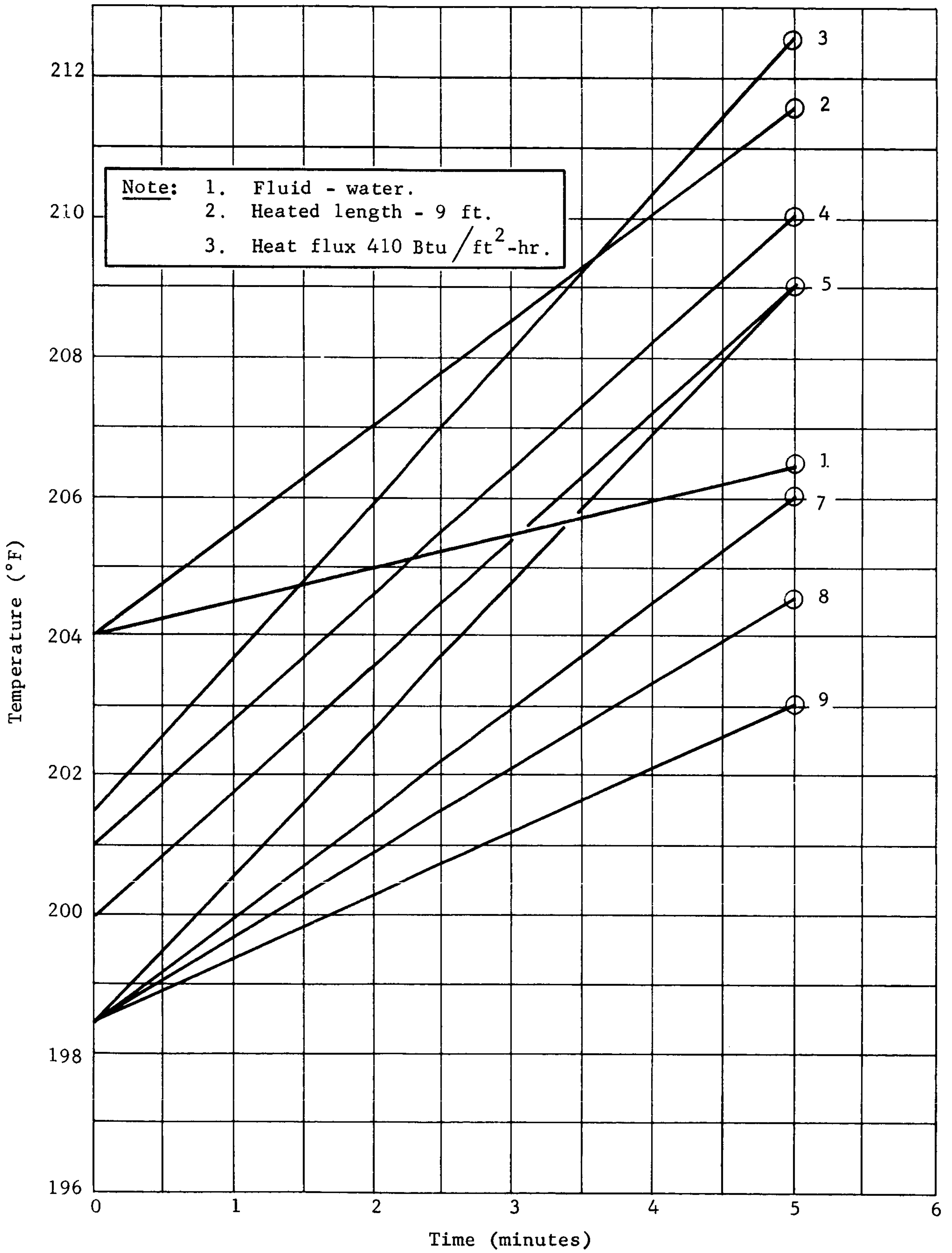

Fig. 13 Fluid Temperature, Time Curves - Test 7

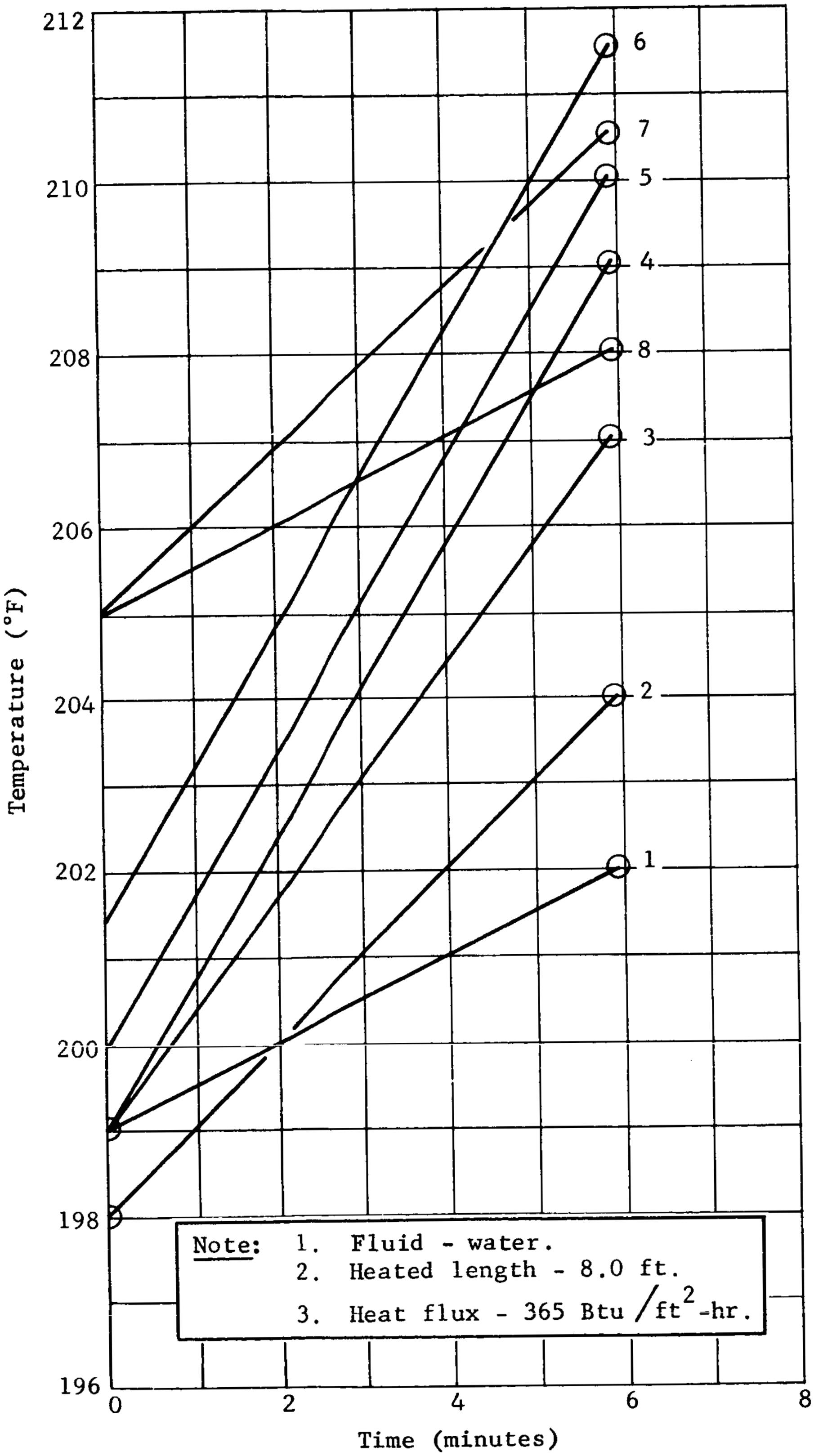

Fig. 14 Fluid Temperature, Time Curves - Test 12

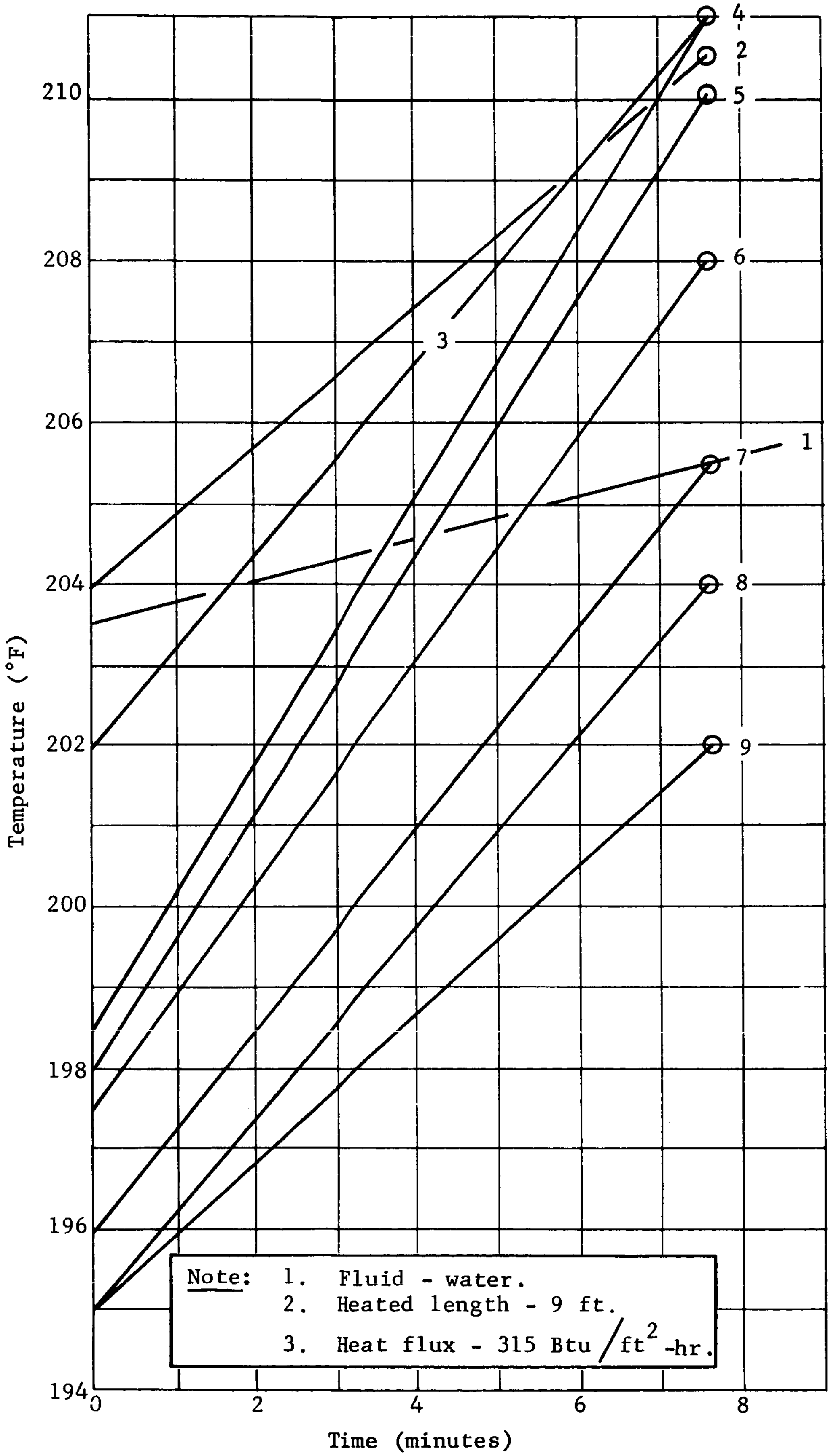

Fig. 15 Fluid Temperature, Time Curves - Test 18

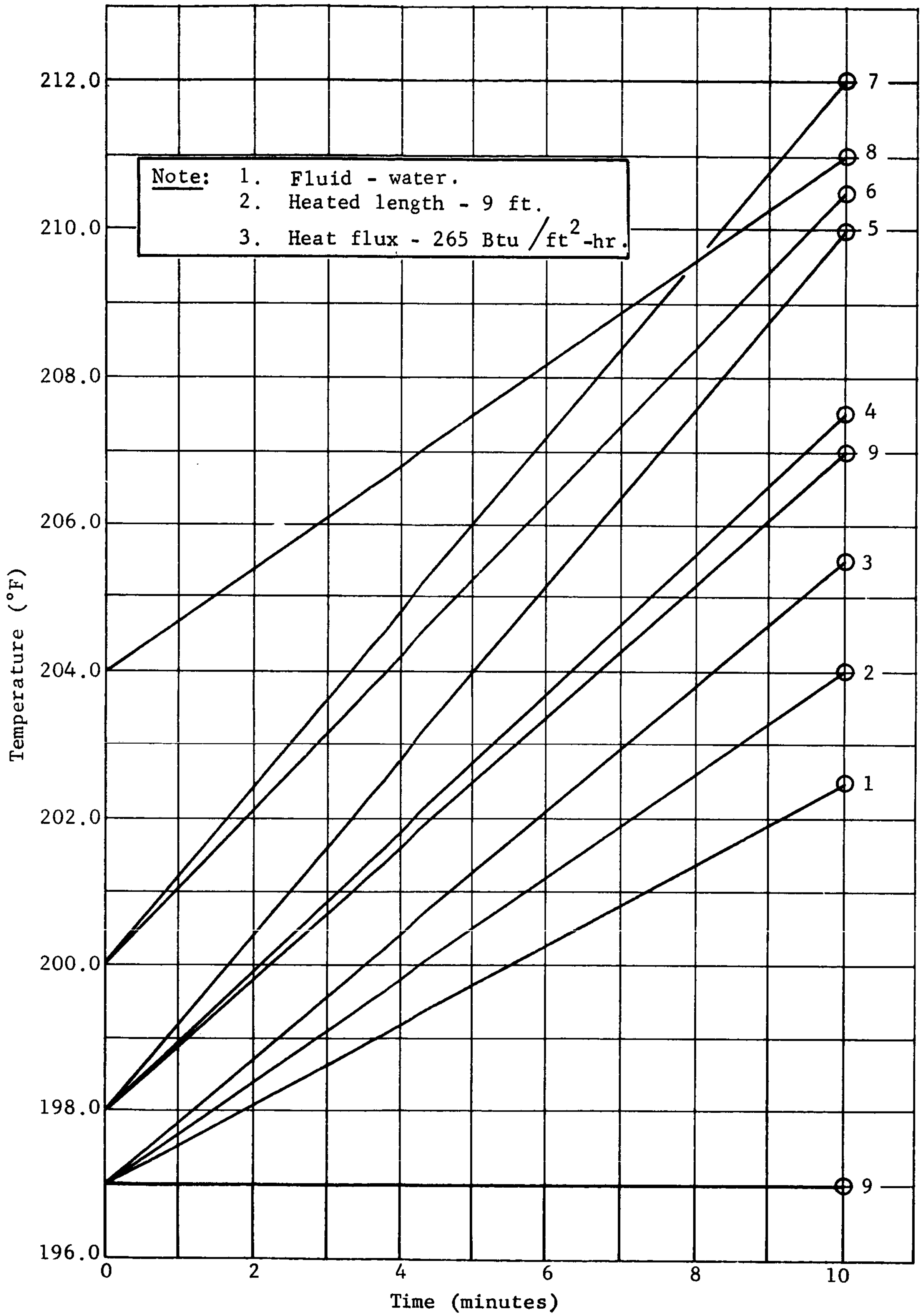

Fig. 16 Fluid Temperature, Time Curves - Test 23

3) Nonuniform heating of the geyser tube;

4) Concentric tube within the geyser tube.

The first method was evaluated with geyser Tube B 6-ft long, using water as the test fluid. A nichrome heater was mounted at the base of the geyser tube, and the radiation heating system was used to heat the geyser tube wall. The base heater was powered by means of a 110-volt variable transformer that provided a means of adjusting the base heater power. Three wall heat fluxes (410, 365, and 315 Btu/ft^2-hr; each heat flux providing a geysering condition) were used, and the heat flux through the base heater was varied from about 50 to 100% of the tube wall heat flux. A total of 9 tests were conducted.

The second method was evaluated with the same geyser tube, but liquid nitrogen was utilized as the test fluid. The tube was insulated with 1/2-in. polyurethane foam resulting in a tube wall heat flux of approximately 85 Btu/ft^2-hr. A length of 3/4-in. diameter aluminum tube was attached to the base of the geyser tube. This 3/4-in. tube was left uninsulated to promote bubble production and thereby increase mixing in the geyser tube. A total of 3 tests were conducted using 3/4-in. tube lengths of 4 ft, 2 ft, and 6 in.

The insulation was then removed from the geyser tube and 3 additional tests were conducted with liquid nitrogen and 3/4-in. tube lengths of 3, 8, and 24 in.

The third method was to attempt to increase fluid circulation and thereby suppress geysering by producing boiling inside the geyser tube at a single point on the circumference by means of a fin on the outside of the geyser tube. Geyser Tube B, 6 ft long, was insulated with 1/4-in. foam, and a 2 x 0.010-in. aluminum fin was installed along the full length of the tube. The test fluid utilized was liquid nitrogen. One test was conducted with this apparatus.

The final method of geyser suppression investigated was the use of a concentric tube within the geyser tube. The intent of the concentric tube was to provide boiling in the annulus and thereby reduce the heat flux to the fluid in the inner tube and to stimulate circulation from the inner tube through the annulus. Geyser Tubes A, B, and D were used in the investigation. Water heated by the heat lamp system was used with Tube A and liquid nitrogen was used with Tubes B and D. Table 3 presents a summary of the tests conducted.

Table 3 Test Summary, Concentric Tube Geyser Suppression

Geyser Tube	Heated Length (ft)	Heat Flux (Btu/ft^2-hr)	Concentric Tube Length (ft)	Annulus Width (in.)
A	6	~400	6	1/4
			5	
			4	
			3	
			2	
			6	1/2
			5	
			4	
			3	
			2	
		~300	2	1/2
		~200	2	1/2
	7	~400	3	1/2
	8	~400	3	1/2
B	6 1/2	~ 85	3	1/2
	6 1/2	~ 85	2	1/2
D	12	~700	10	7/8

2. Geyser Suppression Test Results

Base Heating - The suppression tests conducted with a heater at the base of the geyser tube indicated that the convection process within the tube is different than without base heating. The base heating resulted in an increased geyser period; however, in no case did the base heating eliminate geysering. Because the complete elimination of geysering was not possible, this method was rejected as a possible means of suppressing geysering.

Horizontal Tube - The first series of tests using geyser Tube B 6-ft long and 1/2-in. foam indicated that this method may be feasible. Each of the three 3/4-in. tube lengths tested was successful in suppressing geysering. The second series of tests without the insulation resulted in geysering independent of the 3/4-in. tube length. These results show that the method may or may not be feasible and suppressing geysering depends on the specific geyser tube conditions. The parameters investigated in these tests were certainly not complete and additional study may prove this method to be desirable. This method was not investigated further because it appeared that considerably more effort than was available in the program was required to prove the feasibility.

Concentrated Heat Flux - The use of a fin to concentrate the heating at one point on the circumference of the geyser tube had no effect on the geysering. The geyser period and geyser violence was the same with or without the fin. This method was also discarded because again the development effort required seemed to be in excess of the time available.

Concentric Tube - The concentric tube was effective in eliminating geysering in Tube A with a heated length of 6 ft until the concentric tube length was reduced to 2 ft. At this point, the tube geysered. The results were the same for an annulus width of 1/4- and 1/2-in. Also the results were the same when the heat flux was reduced from 400 to 200 Btu/ft^2-hr. The geyser tube heated length was increased to 8 ft, which provided a geyser length as determined from the correlation below the concentric tube. With a geyser length below the concentric tube geysering occurred, indicating the concentric tube had no effect.

The tests with liquid nitrogen showed that for a geyser tube of 4-in. diameter, the concentric tube would suppress geysering until the concentric tube length was reduced to 2 ft.

The test on the 8-in., 12-ft long geyser tube with liquid nitrogen, showed that a concentric tube of 10-ft would not suppress geysering. The result from the 8-in. tube is inconsistent with the results from the 4-in. tubes showing that a suitable geyser suppression method was not developed. Again, this method was not investigated further because of lack of time.

From a geyser suppression standpoint, the concentric tube method seems to be the most promising of all the methods studied. Even this method, however, still requires a substantial effort to develop a workable system.

IV. CONCLUSIONS

A satisfactory correlation has been developed for the prediction of geysering in terms of heating rate, system geometry, and fluid properties. The correlation was developed for a range of variables encountered in missile design. This correlation can be used in the design of missile suction lines to prevent geysering or assist in eliminating geysering in existing systems.

None of the geyser suppression methods studied appear to be completely satisfactory. Two of the methods, a horizontal tube at the geyser tube base and a concentric tube in the geyser tube, were successful under certain conditions of suppressing geysering and may prove useful for some specific applications.

Additional work is required to extend and gain a better understanding of the horizontal tube and concentric tube methods of suppression. Additional horizontal tube diameters and lengths should be studied. Also, additional studies should be undertaken to understand the mechanism involved in the concentric tube method.

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